

Thermosphere-Ionosphere-Mesosphere Modeling Using the TIME-GCM

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LONG-TERM GOALS

A major goal of the research is to understand how elements in the coupled upper atmosphere/ionosphere system interact with one another and to determine how this coupled system responds to the variable energy input from the sun and the variable input from the lower atmosphere and ocean. The research focuses on understanding the sources and characteristics of global-scale ionospheric, thermospheric, and mesospheric structure and variability and the coupling of those atmospheric regions to the lower atmosphere and then to the magnetosphere and solar wind.

SCIENTIFIC OBJECTIVES

Our scientific objectives are to understand the nature of the sources of variability in the upper atmosphere/ionosphere system and how they are related to solar radiative and auroral particle and electric field forcings. We are also interested in understanding how disturbances from the lower atmosphere and ocean affect the upper atmosphere and how this variability interacts with the variability generated by solar and auroral sources. We accomplish this task by developing large-scale numerical models of the upper atmosphere and ionosphere and using these models to analyze data obtained by satellites and ground-based observatories as well as using these models for numerical simulations to understand how upper atmosphere/ionosphere physics and chemistry interact. We are also developing and using a model of the whole atmosphere extending between the ground and 500 km for use in simulating and analyzing atmospheric variability and for studying solar and auroral influences on the entire atmosphere. This model, once fully developed and verified, will be useful for predictions of atmospheric circulation, temperature and compositional structure, space weather and global change.

APPROACH

A hierarchy of numerical models has been developed that describes the upper atmosphere and ionosphere and these models have been used to study atmosphere/ionosphere interactions and their response to solar and auroral variability for over 25 years. The current version of models include: the TIE-GCM, TIME-GCM, and flux-coupled TIME-GCM/CCM3, where T, I, M, and E represent “thermosphere,” “ionosphere,” “mesosphere,” and “electrodynamics,” respectively. The CCM3 is the NCAR Community Climate Model, Version 3.6, a GCM of the troposphere and stratosphere. All models include self-consistent ionospheric electrodynamics, that is, a calculation of the electric fields

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14. ABSTRACT A major goal of the research is to understand how elements in the coupled upper atmosphere/ ionosphere system interact with one another and to determine how this coupled system responds to the variable energy input from the sun and the variable input from the lower atmosphere and ocean. The research focuses on understanding the sources and characteristics of global-scale ionospheric, thermospheric, and mesospheric structure and variability and the coupling of those atmospheric regions to the lower atmosphere and then to the magnetosphere and solar wind.					
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and currents generated by the ionospheric dynamo, and consideration of their effects on the neutral dynamics. The TIE-GCM is used for studies that focus on the thermosphere and its coupling with the ionosphere and magnetosphere. The TIME-GCM, the most elaborate of the upper-atmospheric TGCs, solves for global distributions of neutral and plasma temperatures, velocities, and compositions, including all of the species that are photochemically important in the upper stratosphere, mesosphere, thermosphere, and ionosphere. The flux-coupled TIME-GCM/CCM3 is an exploratory climate model that extends from the ground, including oceans, to 500 km altitude to study global atmospheric variability and couplings.

A project that is in its third year is to extend the current NCAR Climate Systems model to include the thermosphere and ionosphere up to an altitude of 500 km. This Whole Atmosphere Community Climate Model (WACCM) is a continuous model of the entire atmosphere compared with the flux-coupled TIME-GCM/CCM3 where 2 independent models are coupled at a free surface in the atmosphere (10mb). It has become our basic model that will eventually absorb all of the capabilities of the other existing models.

In addition to the above models we also use the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) to provide auroral inputs and a Global Scale Wave Model (GSWM) to study tides and planetary wave propagation in the atmosphere. The latter is a linearized model that is useful in helping understand tidal and wave phenomena in the non-linear TGCs. We also have a small-scale gravity wave model to examine processes and develop parameterizations of these processes for inclusion in the global models.

NCAR personnel participating in this work include: Raymond G. Roble (aeronomy and global upper atmosphere and ionospheric dynamics), Arthur D. Richmond (electrodynamics and upper atmosphere waves), Hanli Liu (gravity wave parameterizations), Maura E. Hagan (tides and planetary waves), Barbara A. Emery and Gang Lu (campaign studies and data analysis), and Benjamin Foster (programming support and model development). The Whole Atmosphere Community Climate Model (WACCM) is a collaborative effort between three NCAR Divisions: The High Altitude Observatory (HAO), The Climate and Global Dynamics Division (CGD), and the Atmospheric Chemistry Division (ACD).

WORK COMPLETED

Completed the TIE-GCM rewrite. The new model, tiegcm1, uses a dynamic 2-d data decomposition with MPI for parallel execution and support for two spatial resolutions in both the horizontal and vertical. The code can run with 5 degree latitude and longitude resolution with 2 grid point per scale height vertical resolution or 2.5 degrees latitude and longitude with 4 grid points per scale height. This code is now in production, and is scaling up to 32 processors on the NCAR IBM machines. The code was frozen on 11/8/03. Major additions so far include the import of GSWM tidal boundaries, use of the Weimer model for high latitude electric potential, and assimilation of AMIE data. The data input and output structure has been changed to netcdf format.

Within the past year the dynamics and chemistry have been fully coupled in WACCM allowing self-consistent interactions to be examined throughout the troposphere, stratosphere, mesosphere and lower thermosphere. The dynamical model is based the Climate Systems Model at NCAR but it has been extended to include molecular diffusion, a gravity wave spectrum parameterization, non-LTE radiation

processes and a finite volume dynamical core. The interactive chemical model also uses a finite volume core in the MOZART framework but has been updated to include additional processes needed to represent the lower thermosphere, including ion-molecule reactions, auroral NO_x production and NO cooling. Other chemical and dynamic components needed for the upper mesosphere and lower thermosphere have been taken from the TIME-GCM. The new fully coupled WACCM has been run for over 50 years using time-varying sea surface temperature and significant El Niño/La Niña effects have been noted throughout the middle atmosphere as discussed in the next section.

A satellite track processor has been developed to sample model data along any satellite track and analyze data in terms of ascending and descending orbit node differences. Our simulations show that a significant aliasing can occur for various tidal components, e.g. migrating and nonmigrating diurnal and semidiurnal components into tidal fields of observed zonal wavenumbers greater or equal to zero. Aliasing can also occur in the temperature and compositional fields that need to be considered when attempting to reconcile differences between model tidal components and observed fields. We have also updated other processors for ease in comparison with ground based and satellite data.

Various aeronomic components in the TIME-GCM have also been added. These include 4.3 micron CO₂ heating by solar radiation, updates to the rate coefficients used in the non-LTE CO₂ radiational component and NO non-LTE cooling in the thermosphere, various quenching coefficients and chemical reaction rates. NO self-absorption of solar radiation and energetic solar proton energy deposition and ionization have also been updated.

RESULTS

The results from some of the studies conducted during the past year include the following:

Airglow Variability in the Mesosphere and its Relationship to Convective Forcings: The High Resolution Doppler Imager on the UARS satellite has observed the O₂ atmospheric band nightglow at extremely high spatial resolution of 50 km in the horizontal over much of the Earth's surface. These observations of the oxygen nightglow are shown to be a good surrogate for atomic oxygen outflow from the thermosphere and subsequent recombination in the upper mesosphere. The distribution of enhanced airglow and recombination indicate that bright regions of the nightglow are associated with descending motion where tides are transporting atomic oxygen out of the thermosphere and regions of decreased airglow are associated with ascending of tidal motion. The detailed observations of the global airglow at a scale of 100 km present a much more complex picture, however. These structured regions are present over the entire nightside of the globe and can be persistent on a time scale of a day or more. Simulations with the TIME-GCM show that these bright airglow patches are related to gravity wave forcing in regions of preferred convection and are a major source of the variability observed in the MLT region. These results illustrate the strong coupling between the lower atmosphere and ocean with regions high in the Earth's atmosphere.

Southern Hemisphere Stratospheric Warming in 2002: The TIME-GCM was run for the entire year 2002 and histories were recorded hourly throughout the year. The year was selected so that model simulations could be compared directly with satellite data, such as that obtained from the TIMED, UARS and ARGOS satellites. The model simulations indicate that strong wave forcings in the southern hemisphere winter led to a major stratospheric warming in September 2002 including a major breakup of the stratospheric ozone hole. The model showed that the strong stratospheric warming was

accompanied by a strong mesospheric cooling and a change in the circulation in the high latitude winter mesosphere. The warming event also affected the mesospheric airglow layers, chemical composition and tidal and planetary wave propagation. This event is being studied and the results compared with satellite and ground-based observations in hopes of better understanding the overall physics and chemistry and the coupling between atmospheric regions. Overall the event appears to be similar to an event studied in detail by Liu and Roble (2002). That stratospheric warming was simulated in the coupled TIME-GCM/CCM3 and was described in last year's report. A paper on the current event is in preparation.

Long-lasting Disturbances in the Equatorial Ionospheric Electric Field: The Magnetosphere-Thermosphere-Ionosphere-Electrodynamics General Circulation Model has been used to investigate ionospheric-wind-dynamo influences on low latitudes ionospheric electric fields during and after a magnetic storm. The simulations were performed with time-varying polar cap electric potentials and an expanding and contracting polar cap boundary. Three influences on equatorial electric fields were noted to have comparable importance: (1) global winds driven by solar heating; (2) direct penetration of polar cap electric fields to the equator that are partially shielded by the effects of Region-2 field-aligned currents; and (3) disturbance winds driven by high-latitude heating and ion-drag acceleration. The simulations support the theories of the so called "disturbance dynamo" and "fossil wind," both of which predict long-lasting disturbances in the equatorial eastward electric field associated with magnetic storms.

Thermospheric Simulations of the Geomagnetic Storm of April 2002: Simultaneous ground-based optical observations of the response of the thermosphere to the geomagnetic storm of April 2002 were made by Gonzalo Hernandez at the South Pole and Arrival Heights, Antarctica. Large meridional and zonal winds were observed reaching 600 m/s. The kinetic temperature during the storm showed an increase of 3-fold from normal values of 1000K prior to the storm to 3000K during the storm. 630nm airglow emissions also increase nearly 20-fold during the storm. The TIME-GCM simulations for the event showed that good agreement with the data could be obtained with the inclusion of a large flux of soft electrons bombarding the polar cap and auroral zone. A storm on this magnitude undoubtedly had a significant influence on satellite drag as well as significant ionospheric effects.

Sea Surface Temperature (SST) Effects on the Structure and Composition of the Middle Atmosphere: A simulation of the structure and composition of the middle atmosphere was made using the Whole Atmosphere Community Climate Model (WACCM) forced at the lower boundary with observed sea surface temperature for the period 1950-2000. This period contains several instances of anomalously warm/cold tropical SST, which are identified using the NINO3 index. The simulations reveal anomalies in the structure of vertically propagating planetary waves from the troposphere to the mesosphere. Circulation anomalies in the middle atmosphere are accompanied by large temperature anomalies that are of opposite sign in the stratosphere and mesosphere, the stratosphere being warmer during El Niño events, whereas the mesosphere is colder. Near the summer mesopause, an anomalous source of momentum due to parameterized gravity waves results in warming during El Niño. Compositional differences during El Niño/La Niña events also occur with more ozone depletion occurring during La Niña.

Web site for the Thermospheric General Circulation Models:

<http://www.hao.ucar.edu/public/research/tiso/tgcm/tgcm.html>

Web site for the AMIE electric potential patterns for selected space weather events:

http://www.hao.ucar.edu/public/research/tiso/amie/AMIE_head.html

Web site for the January 97 TIE-GCM movies:

http://www.hao.ucar.edu/public/research/tiso/tgcm/jan97_movies/jan97_movies.html

Web site for WACCM:

<http://acd.ucar.edu/models/WACCM/>

IMPACT/APPLICATIONS

The models we have developed are community models and they have been used by over 100 scientists and students over the past years. Thus, the models are constantly being evaluated, upgraded and improved by community feedback. We participate in NRL studies, NSF Coupling and Energetics of Atmospheric Regions (CEDAR), Geospace Environmental Modeling (GEM), and Space Weather Initiative (SWI) programs. The models have been used for the Navy ARGOS satellite mission, the NASA Sun-Earth Connection Theory Program, the Atmosphere Explorer (AE), Dynamics Explorer (DE), Solar Mesosphere Explorer (SME), Upper Atmosphere Research Satellite (UARS), the Global Geospace Study (ISTP/GGS), and the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) NASA satellite missions as well as U.S. Air Force and Navy satellite missions. We have also participated in the CRISTA and MAHRSI space shuttle experiments. We also participate in the NCAR Climate Systems Modeling effort in examining the couplings between the upper and lower atmospheres and in an attempt to understand the effects of the variable solar outputs on the coupled Earth system. We have also developed a model of the whole atmosphere (WACCM) that is useful for studying couplings between the atmosphere and ocean and the response of the entire atmosphere to solar-terrestrial couplings.

RELATED PROJECTS

The numerical modeling effort is complemented by a data analysis and interpretation effort. Data from the following satellites have been analyzed and compared with model simulations:

Navy ARGOS Satellite Mission

NASA Dynamics Explorer Mission

NASA Upper Atmosphere Research Satellite (UARS)

NASA CRISTA and MAHRSI Experiments On Board the Space Shuttle

NASA Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) Satellite

NASA ISTP/GGS Satellite Mission

NSF CEDAR Campaigns

NSF GEM Campaigns

HONORS/AWARDS/PRIZES

Raymond G. Roble was designated “Highly Cited Researcher” by ISIHighlyCited.com for his influence in the category of Space Sciences as measured by citations to his work. Those cited comprise less than one-half of one percent of all publishing researchers. Further information can be found at <http://isihighlycited.com>

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PRESENTATIONS IN FY2003:

Longitudinal variability of tides in the mesopause region, M. E. Hagan, J. M. Forbes, and R. G. Roble, paper presented at the PSMOS meeting, Foz do Iguacu Brazil, October 7-10, 2002.

Equinox transition in wind and airglow observations, G. G. Shepherd, W. Singer, J. Stegman, and R. G. Roble, paper presented at the PSMOS meeting, Foz do Iguacu Brazil, October 7-10, 2002.

The altitudes of polar mesospheric clouds at South Pole, C. S. Gardner, X. Chu, W. Pan, and R. G. Roble, invited paper presented at the COSPAR meeting, Houston, TX, October 10-19, 2002.

Global decline in thermospheric density: Indications of integrated effect of greenhouse cooling through the middle and upper atmosphere, G. M. Keating, M. E. Theriot, Jr., R. H. Tolson, S. W. Bougher, R. G. Roble, and R. A. Akmaev, paper presented at the COSPAR meeting, Houston, TX, October 10-19, 2002.

Gravity wave transport near the upper mesosphere, F. Sassi, D. Kinnison, B. A. Boville, R. R. Garcia, and R. G. Roble, invited paper presented at the AMS Middle Atmosphere meeting, San Antonio, TX, November 4-8, 2002.

An overview and science results from the SABER experiment on the TIMED satellite, J. M. Russell III, M. G. Mlynczak, L. L. Gordley, C. J. Mertens, R. H. Picard, M. Lopez-Puertas, P. Wintersteiner, J. Winnick, D. E. Siskind, D. Baker, J. Ulwick, E. E. Remsberg, R. R. Garcia, P. J. Epsy, R. G. Roble, and S. Solomon, invited paper presented at the AMS Middle Atmosphere meeting, San Antonio, TX, November 4-8, 2002.

A Whole Atmosphere Community Climate Model (WACCM) for studying solar-terrestrial interactions, R. G. Roble, R. R. Garcia, B. A. Boville, D. Kinnison, and F. Sassi, paper presented at the LWS workshop, Laurel, MD, November 13-15, 2002.

F2-layer behaviour modelled with coupling from the lower atmosphere, M. Mendillo, H. Rishbeth, R. G. Roble, and J. Wroten, paper presented at the Fall AGU meeting, San Francisco, CA, December 6-10, 2002.

An overview and science results from the SABER experiment on the TIMED satellite, J. Russell, M. Mlynczak, L. L. Gordley, C. Mertens, R. Picard, M. Lopez-Puertas, D. Siskind, D. Baker, J. Ulwick, E. Remsberg, J. Winik, P. Wintersteiner, P. Epsy, R. Garcia, R. G. Roble, and S. Solomon, invited paper presented at the Fall AGU meeting, San Francisco, CA, December 6-10, 2002.

Overview of one aspect of the Sun-Earth connection during the April 2002 events: The “Magnetospheric Driver” chain, T. H. Zurbuchen, J. Kozyra, G. Lawrence, J. Burch, M. Henderson, B. Burke, J. Salah, J. Russell, and R. G. Roble, paper presented at the Fall AGU meeting, San Francisco, CA, December 6-10, 2002.

Global ionospheric response to the April 2002 storm: Tracing the energy flow, G. Lu, A. D. Richmond, R. G. Roble, T. J. Immel, F. J. Rich, D. S. Evans, J. M. Ruohoniemi, M. Pinnock, S. B. Mende, paper presented at the Fall AGU meeting, San Francisco, CA, December 6-10, 2002.

Lower thermosphere dynamics during April 2002, M. Hagan, G. Lu, and R. G. Roble, paper presented at the Fall AGU meeting, San Francisco, CA, December 6-10, 2002.

Ionospheric dynamo currents and magnetic perturbations at the ground and above the ionosphere modeled by the TIEGCM, A. I. Maute, A. D. Richmond, M. E. Hagan, and R. G. Roble, paper presented at the Fall AGU meeting, San Francisco, CA, December 6-10, 2002.

An overview and science results from the SABER Experiment on the TIMED satellite, M. G. Mlynczak, J. M. Russell III, L. L. Gordley, C. J. Mertens, R. H. Picard, M. Lopez-Puertas, D. Siskind, D. Baker, J. Ulwick, E. Remsberg, J. Winick, P. Wintersteiner, P. Epsy, R. Garcia and R. G. Roble, paper presented at AGU/EGS meeting, Nice, France, April 7-11, 2003.

Sampling the NCAR TIME-GCM and GSWM for TIMED and CEDAR related studies, J. Oberheide, M. E. Hagan, R. G. Roble, and G. Lu, paper presented at AGU/EGS meeting, Nice, France, April 7-11, 2003.

Sampling the NCAR TIME-GCM and GSWM for TIMED and CEDAR related studies, and preliminary model/observation intercomparisons, J. Oberheide, M. E. Hagan, G. Lu, R. G. Roble, C. Y. She, T. Yuan, M. Riggins, S. E. Palo, and D. Offermann, paper presented at CEDAR workshop, Longmont, CO, June 15-20, 2003.

On the possible structure of the upper atmosphere at the turn of the century 2100, R. G. Roble, invited paper presented at CEDAR workshop, Longmont, CO, June 15-20, 2003.

TIME-GCM simulations of the 2002 Southern Hemisphere stratospheric warming event, R. G. Roble and H.-L. Liu, invited paper presented at CEDAR workshop, Longmont, CO, June 15-20, 2003.